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Impactor Diameter and Ply Number Effects on the Impact Behavior of Carbon Fiber Composite Laminates

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Abstract

As it is known, impact damage is a major mechanical phenomena for composite materials especially used in the aerospace structures. The factors affecting the impact behaviour of the composites depend on the impactor systems as well as the target material. In this study ply number and impactor geometry effects of carbon fiber reinforced epoxy composites were investigated by low velocity impact tests. In this context, drop weight impact tests were carried out at 6J, 12J and 24J energy levels by using hemispherical impactors with 10 mm and 20 mm diameters. Laminated composites were manufactured in 6, 10 and 14 plies with vacuum infusion method. The effects of laminate thickness, impactor diameter and impact energy on the contact force, velocity, absorbed energy and damage surfaces were investigated and evaluated. It is observed that impactor geometries and velocities caused the different damage mechanisms in composites and impactors played an important role in determining the penetration and perforation behaviours of composites. Increasing impactor diameter increased the penetration and perforation thresholds.

1. INTRODUCTION

Composite materials are widely used in the automotive and aerospace industries [1,2]. However, damage caused by parts, tool falls on the components during maintenance, bird strikes on the landings and takeoffs of aircrafts, hail often result in delamination, matrix cracking and fiber breakage damage to the internal surfaces of composite materials.[3, 4-8]. These damages generally occur as a result of low velocity impacts which defined in the velocity range between 1 m/s and 10 m/s [9]. Drop weight impact tests are a type of low velocity impact tests and based on the principle that a mass hits the specimen as a result of vertical free fall from a certain height. [10,11]. The damage resistance, impact behavior, threshold values for penetration and perforation, impact resistance, absorbed energy, contact forces and damage areas of composite materials are determined with the drop weight impact tests [9, 11-14].

The parameters studied for the low-velocity impact tests are generally consist of the target material related factors such as material thickness/number of layers, material type, specimen geometry and impact test systems factors such as impactor geometry and specimen fixation [2,16]. In this context, Liu et al. [17], investigated the maximum load, maximum displacement, contact time and damage area for one energy level on the impactor geometry. They used the hemispherical and flat tip same diameter impactors. The flat impactor has a higher maximum force, whereas the hemispherical impactor has a larger damage area, longer contact time and greater maximum displacement. They also supported the study with the finite element method. Evci and Uyanan [18] studied the damage behavior of the carbon fiber composites with hemispherical tip impactor at different temperature ranges. The maximum force and delamination area increased with the increase of the impactor diameter. Zhou et al. [19] studied the effects of impact angle, impactor geometry and diameter, and layer arrangement of unidirectional carbon fiber composites. Seifoori et al. [20] studied the low velocity impact behavior of unidirectional glass fiber and carbon fiber composites with spherical, hemispherical and cylinder impactors at two different energy levels. They observed that the largest damage area was caused by spherical impactors, and the damage area increased with increasing impact energy. Guerrero et al. [21] investigated the impactor weight effect on the damage behavior of the

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carbon fiber woven epoxy composites. İçten et al. [22] studied the glass fiber woven epoxy composites at different impactor diameters and different energy levels. The maximum force, and penetration threshold values increased with the increase of the impactor diameter. Reddy et al. [23] studied the effect of different composite thicknesses and different energy levels on low velocity impact behavior of glass fiber laminated composites. As the impact energy and thickness increased, the maximum force and contact time increased. Liao et al. [24] investigated the effects of laminate thickness and different impact energy levels on the impact behavior of z-pinned composites. Fiber breakage turned into the delamination with the increase of laminate thickness. Belingardi et al. [25] investigated the effects of fiber arrangement, composite ply number and different energy levels on the impact behavior of unidirecional carbon fiber composites. Li et all [26] studied the effect of impact energy levels on the pultruded glass fiber rove polyester composites. Qiu et al. [27] investigated the effects of carbon-graphite epoxy composites at different energy levels on the fiber arrangement, sample geometry, ply numbers and impactor geometry such as flat and hemispherical by experimental and finite element method. The maximum force is greater with the flat impactor and the contact time is shorter. The damage of the hemispherical impactor is more than the flat type. Riccio et al. [28] investigated the effect of fiber sequence at different energy levels according to the finite element method. Quaresimin et all [29] investiated the effects of different layer numbers and different fiber sequences of carbon fiber woven epoxy composites on the contact load, absorbed energy and delamination. They stated that the onset damage of delamination and maximum load depended on the laminate thickness. Minak and Ghelli [30] tested unidirectional carbon fiber composites according to the quasi-isotropic fiber sequence at three different energy levels, using two different diameters of circular impactors by experimental and finite element method. The maximum force was estimated by the finite element method and compared with the delamination threshold. The delamination area increased with energy and it has a significant effect on impact behaviour because diameter and boundary conditions affect the stiffness of the target material. Farooq and Myler [31] modeled the effect of 8, 16 and 24 layers of unidirectional carbon fiber composites on the impactor geometry by finite element method. Soto et al. [32] studied the fiber composites at two different impact energies (20J, 30J) by experimentally and finite element method. Wang et al. [33] modeled the delamination behavior of unidirectional carbon fiber composites according to different fiber sequence and different energy levels by finite element method. Gliszczynski et al. [34] carried out impact tests of glass fiber composites according to fiber sequence and different energy levels. Caminero et al. [35] studied the effects of laminate thickness and fiber sequence on different impact energies of unidirectional carbon fiber composites. As the impact energy increased, the damage resistance decreased. Zhou et al. [36] studied the impact behavior of carbon fiber composites at different energy levels by experimental and finite element method. Maximum force, displacement, absorbed energy, delamination area were investigated in simulation. Rio et al. [37] studied the low-velocity impact behavior of unidirectional and woven carbon fiber composites with different fiber sequences and composite thicknesses. Kurşun et al. [38] investigated the low-velocity impact behavior at different energy levels by experimental and finite element method using conical, ogival, hemispherical and flat impactors with a diameter of 12 mm.

Lamina thicknesses which used in aircraft generally vary between 2 and 6 mm, and even their main structures can be under 2 mm thickness [39]. Therefore, in this study different thicknesses carbon fiber laminated composites were manufactured in 6, 10 and 14 plies with vacuum infusion method. It is seen in the literature that impactor geometry played a determining role in the damage mechanisms of the composite materials. For this purpose, effects of ply number and impactor geometry on the low velocity impact behavior of composites were studied and test results investigated with the macroscopic failure images. 6, 12 and 24J energy levels were carried out by using hemispherical impactor tips with 10 mm and 20 mm diameters. Impact energy and impactor shape effects were evaluated together with laminate thickness on the energy abilities of the composites.

2.EXPERIMENTAL STUDIES

2.1. Materials and Manufacturing of the Composites

Plain weave type carbon fiber reinforcements (200gr/m2) supplied by Dost Kimya Company in Turkey and Biresin Sika CR80 epoxy were used as the materials. The epoxy and Sika CH 80-2 hardener mixing ratio was 100:30 by weight. Laminate composites were manufactured in 6, 10 and 14 plies by vacuum infusion method. After the vacuum infusion process, the composites were kept in vacuum for 24 hours. Then the composites were kept in the oven for post-curing at 60 0C for 4 hours. Composite plates were cut according the specimen size. Figure 1 shows the vacuum infusion process setup of composites.

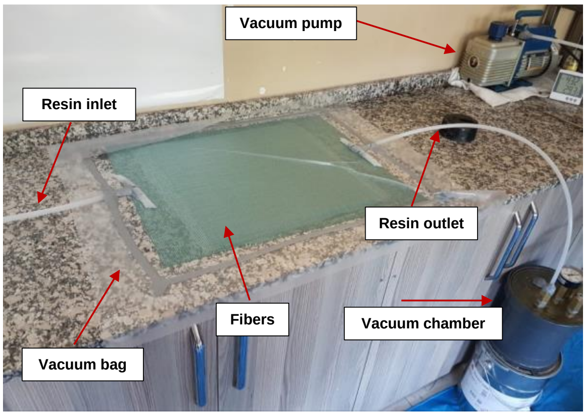

Figure 1. *Vacuum infusion process setup*

2.2 Impact Tests

Drop weight impact tests were carried out with an Instron Ceast 9350 testing machine as the specimen dimensions were 100 mm X 100 mm. The fixture inner diameter is 40 mm and outer diamater is 60 mm. Force, displacement, energy and velocity datas are obtained respect to time at the end of the tests. Acording to the the ASTM 7136 standard [40], the level of impact energy that should be applied to the specimen is E = CE.h, where the CE is 6.7 J/mm and h is the specimen thickness.The impact energies corresponding to 6 ply (1.2 mm), 10 ply (2.17 mm) and 14 ply (3.07 mm) used in this study are 8.04J, 14.54J and 20.57 J respectively. In this purpose, 6J, 12J and 24 J impact energies were applied to each composite sample using the 10 mm and 20 mm diameter hemispherical impactors. Impactors masses are 5.5 kg for both of the impactors. Anti-rebounding system was activated in the tests. Figure 2 illustrates the drop weight test system, impactors and clamping fixture.

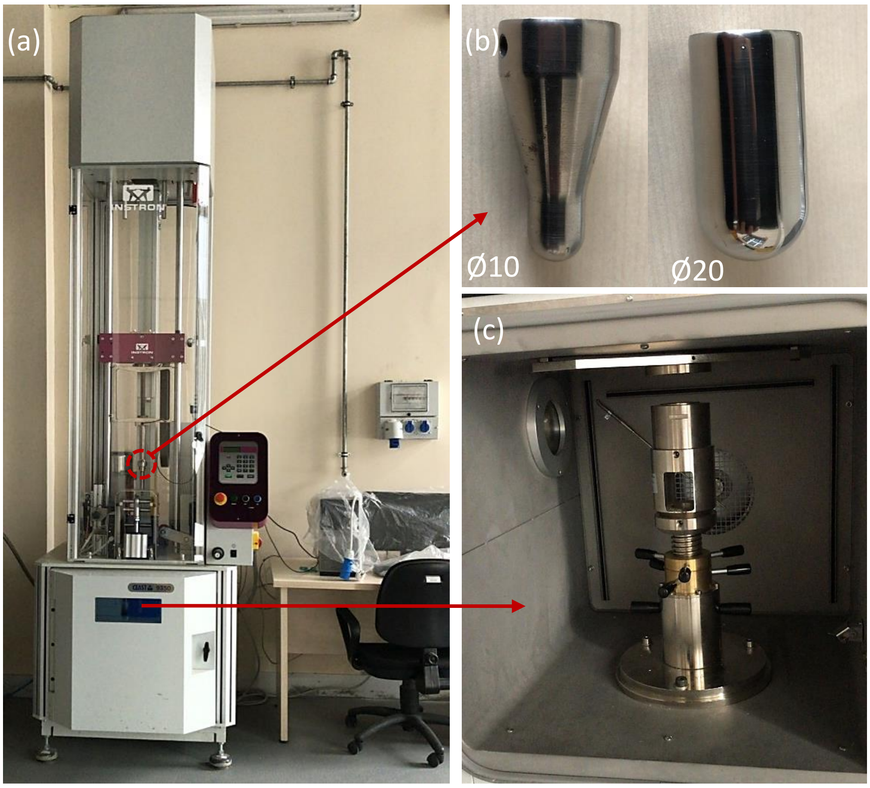

Figure 2. *Drop weight test system: (a) Testing machine, (b) Impactors, (c) Clamping fixture*

3. RESULTS AND DISCUSSIONS

Figure 3-5 show the force-displacement, force-time, energy-time, velocity-time and displacement- time graphics of composites with 10 mm impactor diameter at impact energy levels 6, 12 and 24J, respectively. In the low velocity impact, three situations occur: rebound, penetration and perforation. In the case of rebound, the sample cannot absorb all of the impact energy and this energy spent by the rebound of the impactor from the sample surface. In the case of penetration, all of the impact energy is transferred to the sample when the penetration level is reached and the impactor is stuck in such a way as to cause damage to the sample. In the case of perforation or complete penetration, the impactor pierces the sample through its thickness and exits from the back surface of the sample. The absorbed energy remains constant although the impact energy increases at the perforation level [41-44]. In Figure 3a, the force-displacement curves increase linearly to their maximum value up to the onset of damage with layer thickness which depending on stiffness. Closed curves in the force-displacement graphics show that the composite is not completely penetrated, while open curves have complete penetration of the impactor tip into the specimen [45]. As it is seen from the force-displacement curves in Figure 3a, [C]6 composite is open-ended at 10 mm impactor tip diameter and 6J impact energy. This indicates that the impactor has perforateded the composite. In the [C]6 composite, the load carrying capacity of the composite is lost and the sample is perforated. [C]10 and [C]14 composites show a closed curve. In other words, the damage on the composite that will not cause a penetration by the impactor. As the ply numbers increases, the slope of the curves increases depending on the increase in bending stiffness as it is seen from the force-displacement curves.

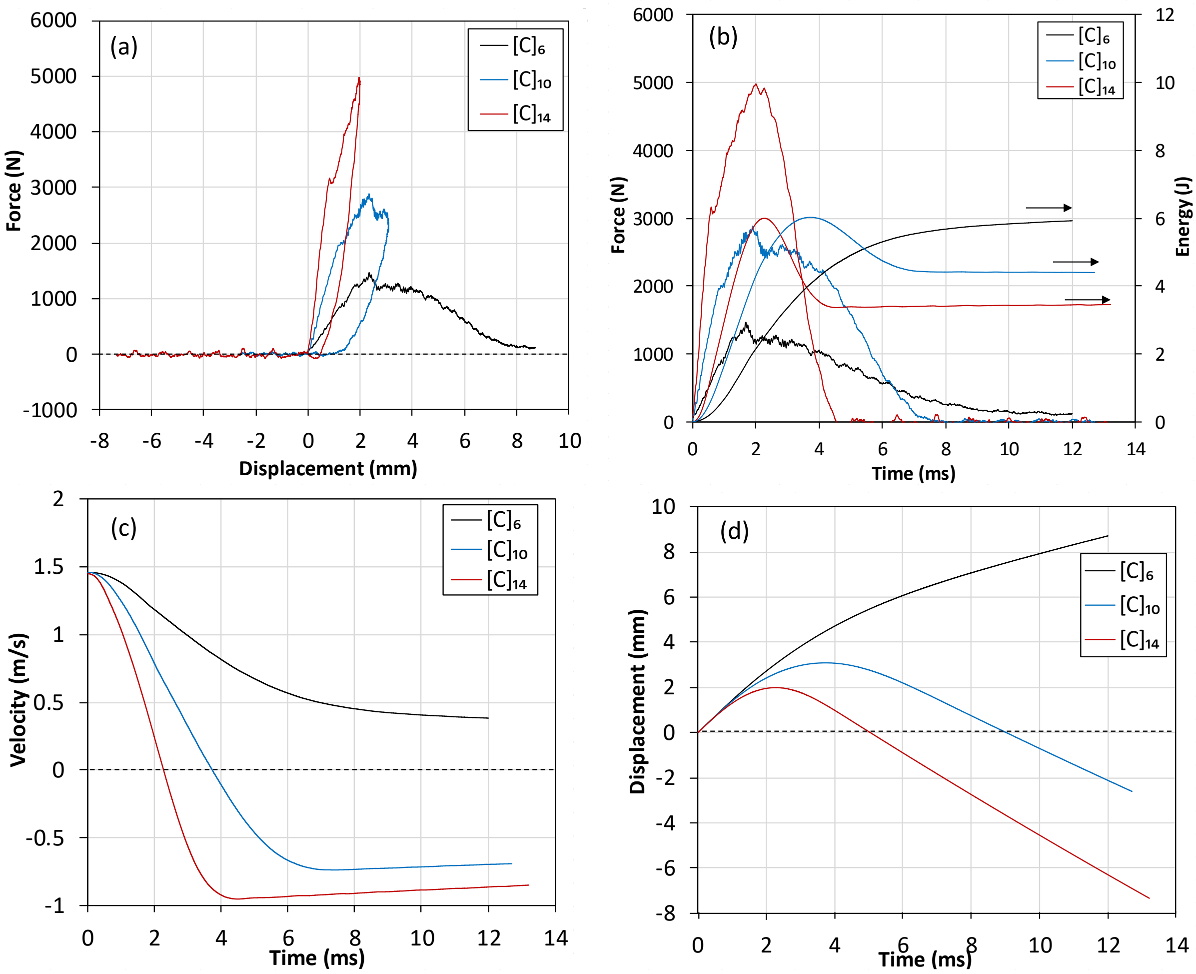

Figure 3. *a) Force vs. displacement, b) Force vs. time and energy vs. time, c) velocity vs. time d) displacement vs. time graphics of composites with 10 mm impactor diameter at 6J impact energy*

In full penetration mode when the 10 mm diameter impactor tip is used, the force decreases in minimum level and then increases again with a (Figures 4a and 5a). In the literature, it has been stated that this situation is caused by the friction between the impactor tip and the composite sample [46]. This friction effect is also reflected in the velocity-time graphs (Figures 4c and 5c). It is seen that the [C]10 composite's energy level goes forward parallel to the horizontal axis (Figure 4b). This shows that the impactor penetrated into the composite. Therefore, the rebound elastic energy of the composite is very low. A closed curve is formed in the force displacement curve of the [C]14 composite, and the impact energy can be absorbed by the composite. By increasing the impact energy to 24J, complete penetration occured in all samples (Figure 5).

Increasing the composite thickness and impact energy increases the contact time. This is also consistent with the literature [17,23].

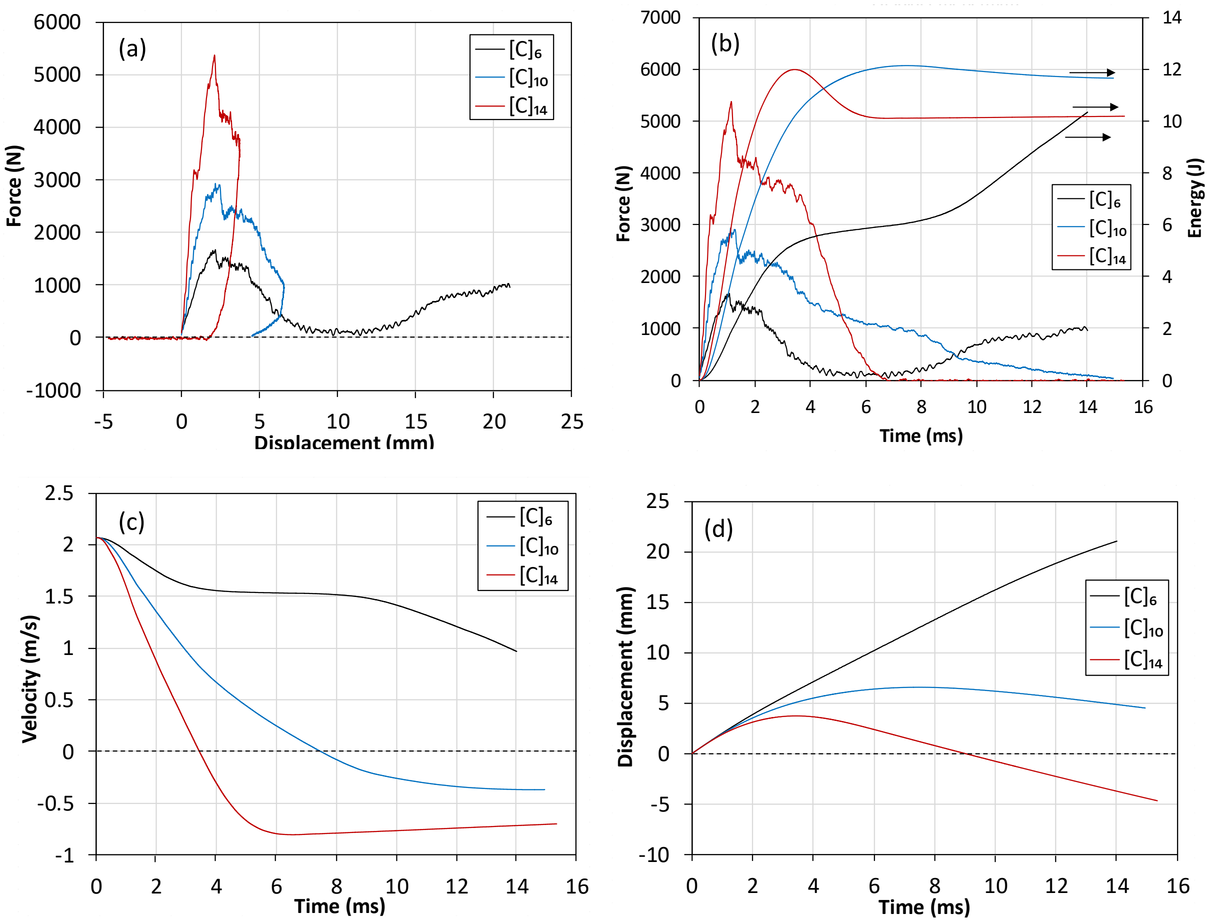

Figure 4. *a) Force vs. displacement, b) Force vs. time and energy vs. time, c) velocity vs. time d)displacement vs. time graphics of composites with 10 mm impactor diameter at 12J impact energy*

When the energy-time graphics of the composites are examined, [C]6 composite shows an increasing trend depending on the time (Figure 3b-5b). The impact energy is equal to the sum of the elastic energy which the sample is not damaged and the energy absorption level when it is damaged. [47]. As a result of the fibers breaking, the energy absorption capacity of the composite is lost. Kinetic energy increases linearly until the impactor completely penetrates (perforation) the specimen and then energy curve continues with a lower trend of increasement after the impactor perforates the sample. If the impactor perforates the specimen, the curve is directed upwards because the region between the impactor and the specimen is subject to friction [48,49]. If the impactor could not complete penetrate the composites, the curves increased to a maximum level up to the impact energy level and then decreased to a constant level by absorbing a certain amount of energy which depending on the rigidity of the composites. As the impact energy increases, the impact duration, maximum force and energy absorption rate increased. This situation is also suitable with the literature. [50]. The perforation energy in composite materials is taken as the energy value when it corresponds to the perforation point where the force values decrease to the minimum level in the open type curves of force-time graph. Then, the energy value continues to increase with the effect of friction between the impactor and the composite [51,52]. In the perforation mode, the energy of the impactor is sufficient to complete penetrate the composite, and some energy is lost due to friction between the composite and the impactor [53]. In other words, perforation occurs in the composites if the impact energy exceeds the penetration threshold [54].

At the velocity-time and displacement-time graphics (Figure 3-5), the velocity approaches the constant value after a certain time due to the perforation of the sample. And also, the displacement increasement continues depending on the time. Since there is a rebound at 6J impact energy in [C]10 and [C]14 composites, most of the applied energy is absorbed. As the number of carbon fiber layers increased, their stiffness increased and the amount of absorbed energy decreased. This shows that thinner composites suffer most of the damage under the same impact energy. Besides, it is seen from the damage photographs that (Figure 9), perforation occurred in the [C]6 composite. As the impact energy increases, the oscillations in the force-displacement curves increase. These oscillations indicate damage formation and propagation, matrix cracking, fiber breakage and delamination [55,56]. In case of rebound of the impactor hitting the composite sample, the velocity of the impactor takes a negative value because it’s direction is opposite to the direction of the impact. If the impactor does not rebound, it indicates that the impactor is stuck in the sample, and after hitting the sample, its speed decreases and continues at a constant horizontal velocity for a certain period of time. Once the maximum displacement is reached, the impactor velocity becomes zero [57]. In Figure 5, it is shown that all the curves continue at the horizontal axis and then they reached to the negative values as the conical part of the impactor.

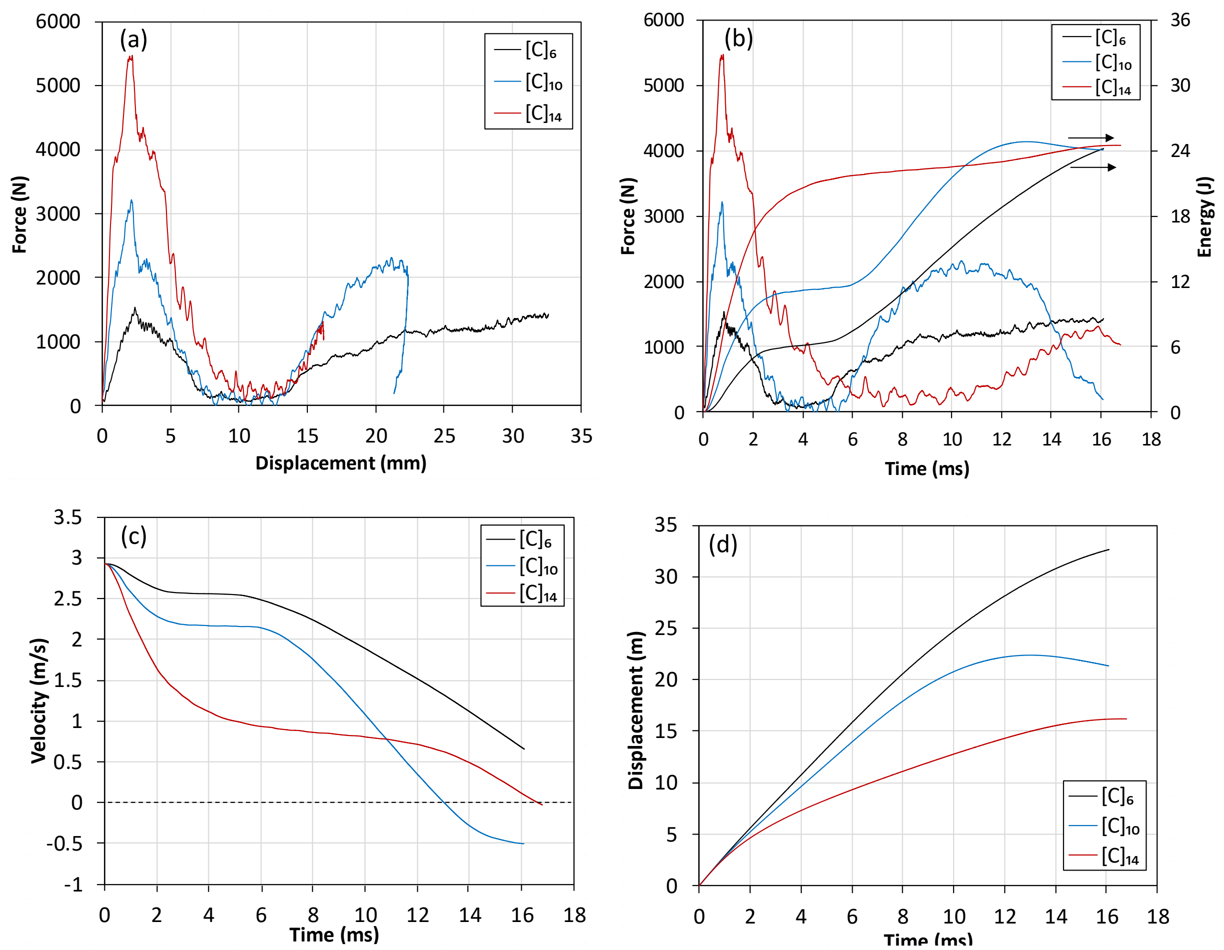

Figure 5. *a) Force vs. displacement, b) Force vs. time and energy vs. time, c) velocity vs. time d)displacement vs. time graphics of composites with 10 mm impactor diameter at 24J impact energy*

In Figures 3d-5d, displacement curves increase to maximum values due to the ability of the composites to absorb energy in rebound situations and move in the negative direction during the rebound of impactor from the specimen. With the increase of impact energy, the curves become steeper from rebound to penetration and perforation modes, respectively. In addition, displacement increases with the increase of impact energy.

As it is seen from the force-displacement and force-time curves (Figure 5), the impactor tip perforated all the composites at 24J impact energy with 10 mm impactor diameter. Because of the12J impact energy level was over the penetration threshold of the [C]6 composite, maximum strength of the [C]6 composite decreased at the 24J impact energy as the load carrying ability of the fibers was lost. Depending on the thickness of the composite, impactor tip continued to perforate the composite in the conical part of the impactor tip at high energy value. When the force dropped to minimum level, 10 mm diameter region of the impactor penetrated the composite. Then there was a force increasement again as the second stage and the conical region of the impactor continued the perforation process. (Figure 5). In the literature, it has been stated that this second force rise is due to the friction between the impactor and broken fibers [58].

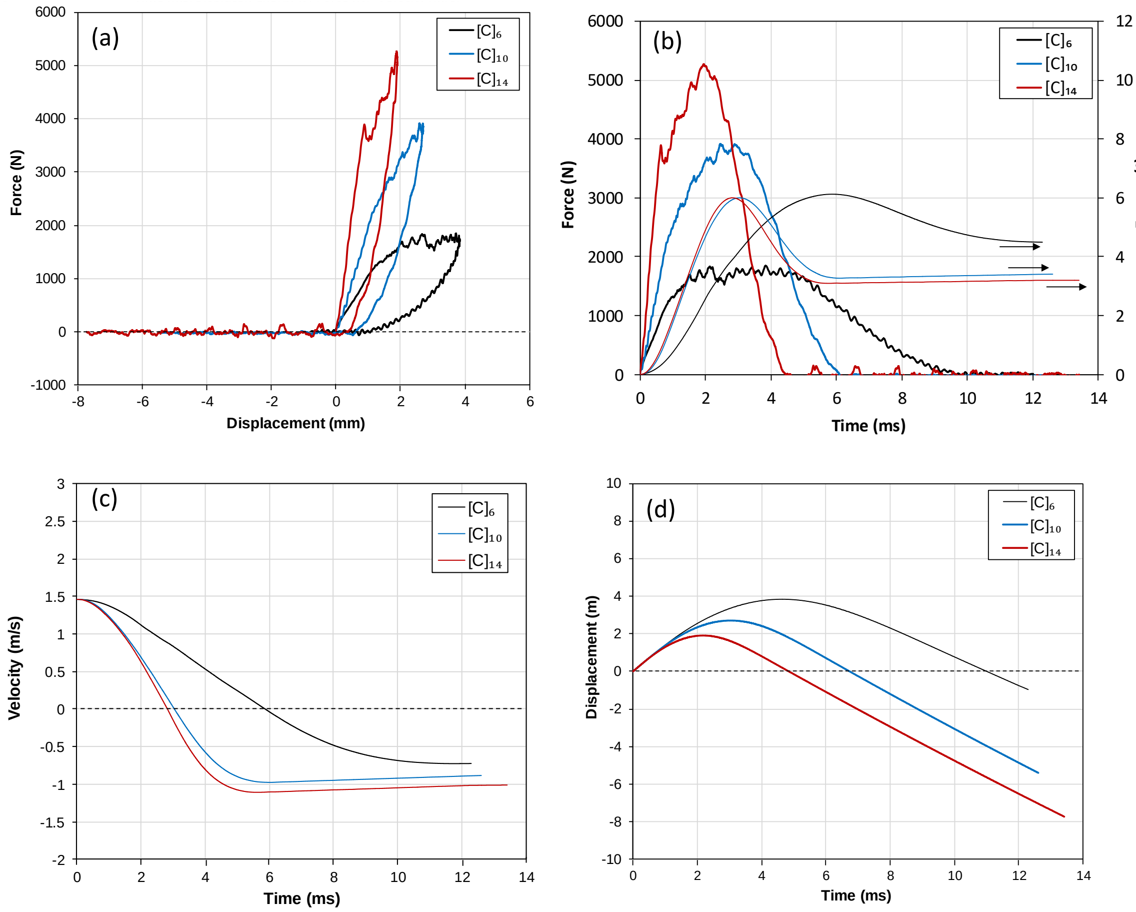

***Figure 6.** a) Force vs. displacement, b) Force vs. time and energy vs. time, c) velocity vs. time d)displacement vs. time graphics of composites with 20 mm impactor diameter at 6J impact energy*

Figure 6-8 show the force-displacement, force-time, impact energy-time, velocity-time and displacement-time graphics of carbon fiber composites with 20 mm impactor diameter at impact energy levels 6, 12 and 24J, respectively. The maximum force values increase with the increasement of the impactor diameter. It is consistent with the literatur [18,22,23]. Therefore, as can be seen from the graphics, the energy absorbing ability of the composites is higher with of 20 mm diameter as the 10 mm diameter impactor exposed to perforation modes at the low energy levels. All the composites showed the rebound behaviour at 6J impact energy.

In Figure 7a, the force-displacement curve in the $[C]_6$ composite shows an open curve and the energy curve tends to increase. It is seen in the energy curve in figure 7b that, $[C]_6$ is in the penetration threshold. Closed curve formation and rebound elastic energy are observed in the force-displacement curves of $[C]_{10}$ and $[C]_{14}$ composites. Increasing of impactor diameter decreased the displacement.

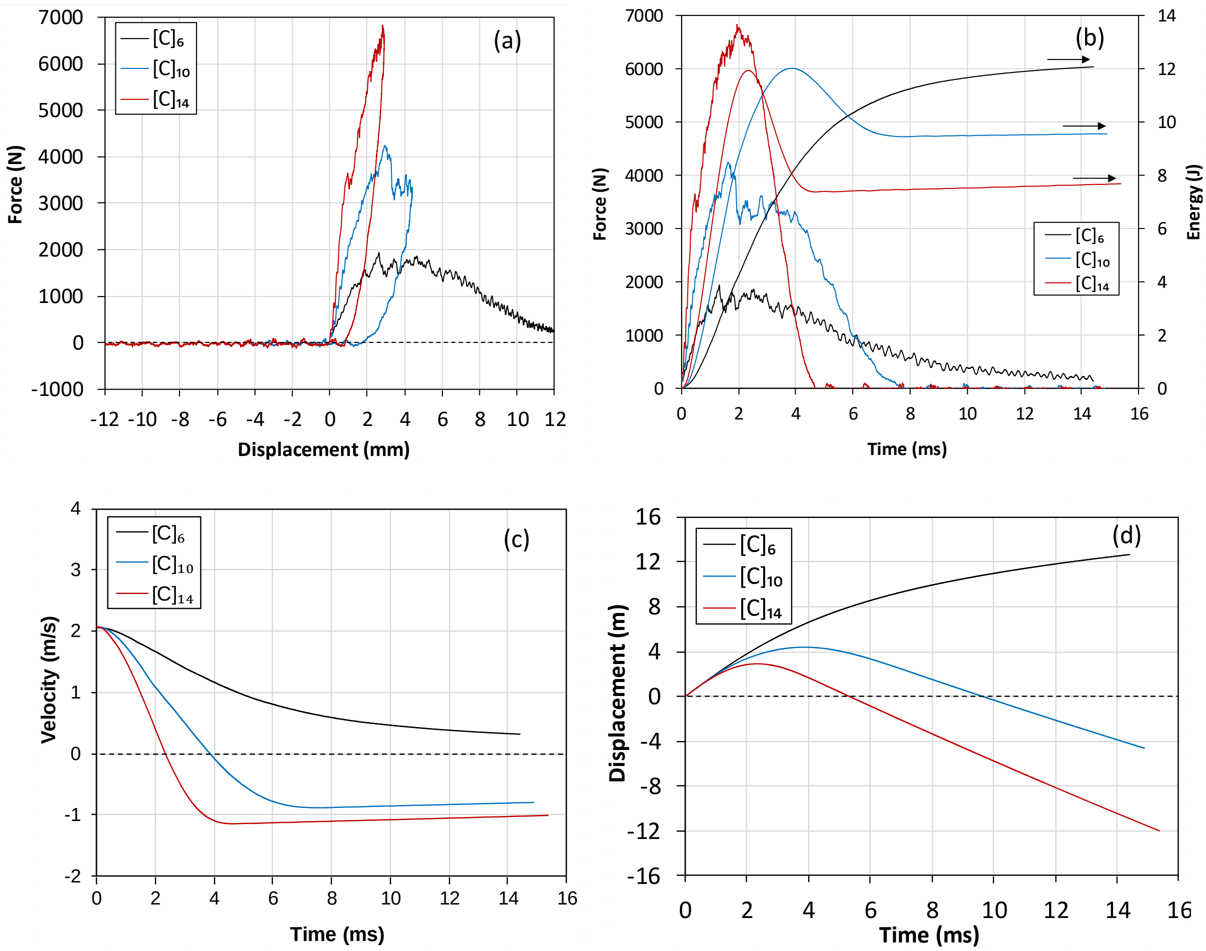

Figure 7. *a) Force vs. displacement, b) Force vs. time and energy vs. time, c) velocity vs. time d)displacement vs. time graphics of composites with 20 mm impactor diameter at 12J impact energy*

In Figure 8, contact force increased with increasing impact energy. Besides in the energy curves, $[C]_6$ was in the perforation mode and $[C]_{10}$ was in the penetration mode. Rebound elastic energy is observed in the $[C]_{14}$. These results consistent with the literatur. Topkaya and Solmaz [59], stated that composite thickness determined the impact performance of carbon fiber composites. Increasing composite sheet thickness increased the contact force and impact strength by decreasing the deformation of composites and so decreased the absorbed energy.

Increasing impact energy increased the displacement. The geometry of the impactor also affects the residual velocity. Rebound velocity of the larger impactor is higher because of the showing less penetration effect than the smaller impactor in rebound modes.

In the $[C]_6$ composite, the impactor displacement goes on linearly due to the perforation. In $[C]_{10}$ and $[C]_{14}$ composites, impactor reaches the maximum displacement at the impact time and then moves to the opposite direction because of rebounding.

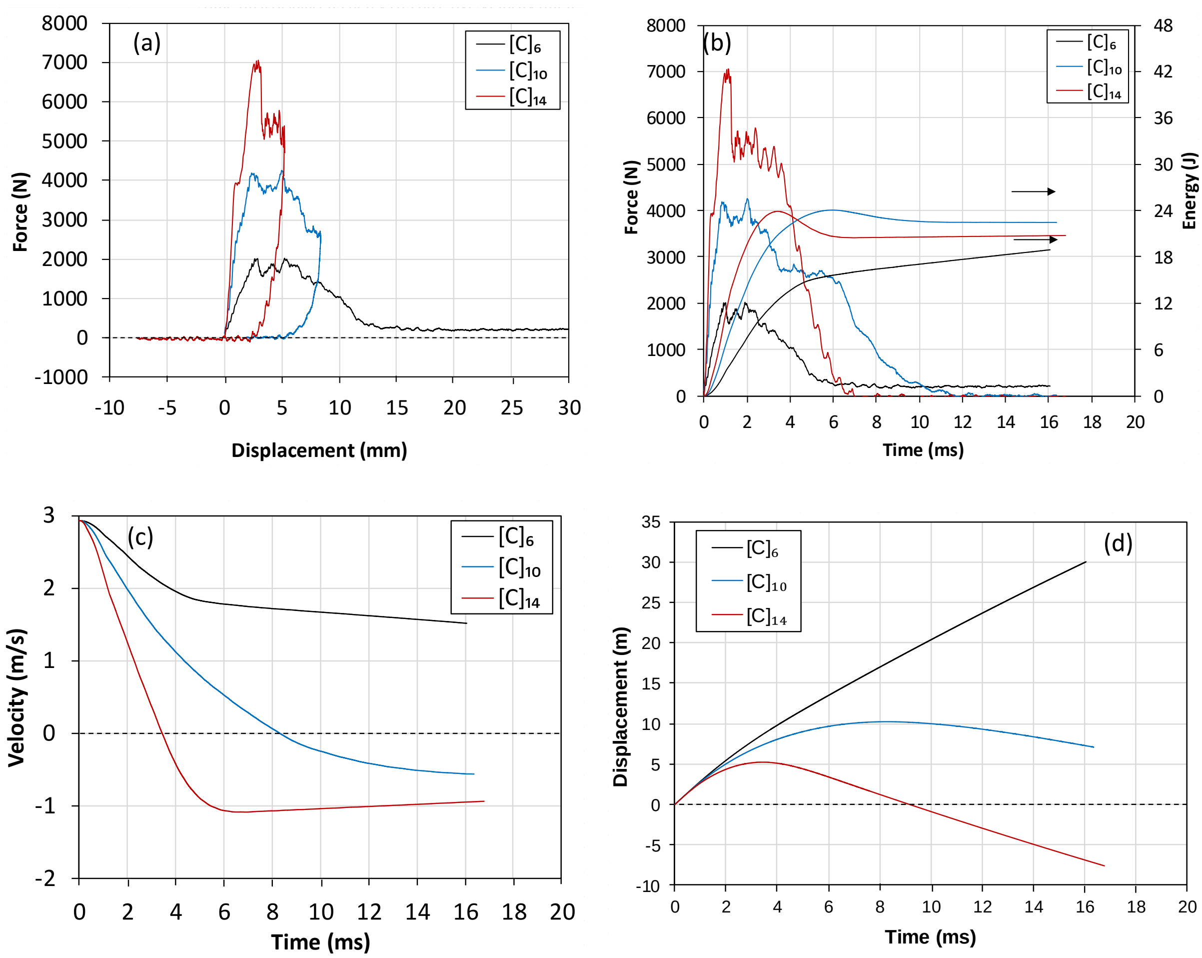

Figure 8. *a) Force vs. displacement, b) Force vs. time and energy vs. time, c) velocity vs. time d)displacement vs. time graphics of composites with 20 mm impactor diameter at 24J impact energy*

Impact damage photographs of the samples according to 10 and 20 mm impactor diameter are given in Figures 9 and 10 respectively. The damage area on the impacted front surfaces is smaller than the back surfaces. As the number of composite layer increases, the damage formation on the composite surfaces also decreases. As can be seen from Figure 9 and 10, the hole width enlarged in the $[C]_6$ composite with the increase of the impact energy. In $[C]_{10}$ composites indented area occured on the front surfaces and fiber breaks occured, a dome-shaped bulge formation occured on the back surface of the $[C]_{14}$ composite. The bulges formed on this back surface are the result of matrix cracking and pull out of the fibers [60]. Increasing composite thickness decreased the fiber breaks. Matrix cracking occured in thermoset composites due to the brittle matrix structure [61]. As the impact energy increased, the penetration damage areas in the composites also increased. Due to the brittle structure of the matrix and fiber, matrix cracking is followed by fiber fractures in the face of impact load with penetration and perforation. It is seen that the interlayers separating increases with increasing impact energies. When compared in terms of impactor diameters, the damage on the composite is greater at small-diameter impactors, because the impact load is concentrated in a smaller area in [56]. On the other hand, the fibers form an outward bulge in the 20 mm diameter impactor, and the splittings which occured between the fibers are less in the composites where the 20 mm diameter impactor is applied. In the literature, it is stated that this splitting was caused by the brittle fracture of carbon fibers [60]. As it is seen in the damage photographs that the penetration effect of the impactor tip is greater due to the local effect of the low-diameter impactor on the impact area at the same energy levels and this situation made the destructive damage to the fibers.

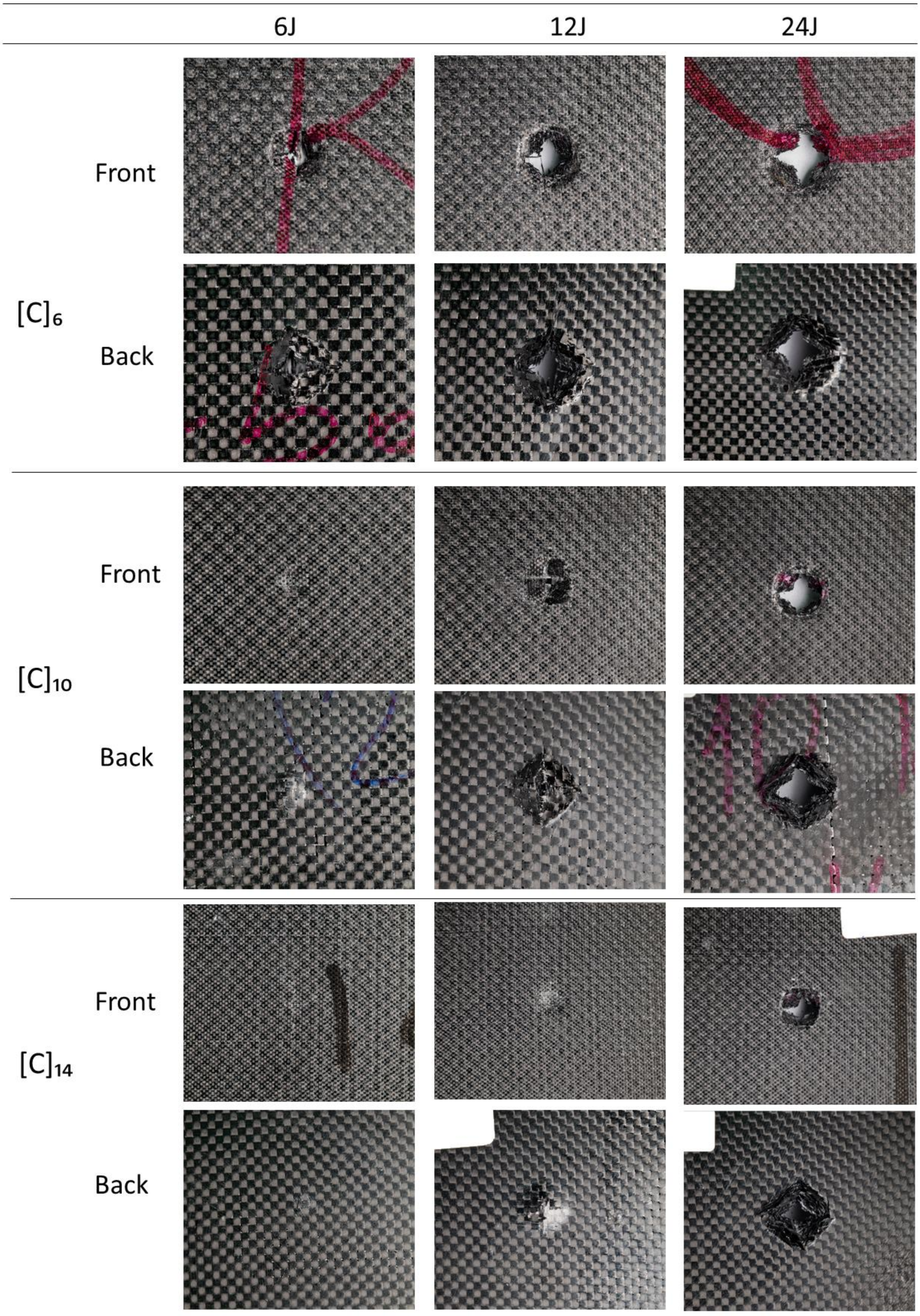

***Figure 9.** Impact damage photographs of the composites with 10 mm impactor diameter*

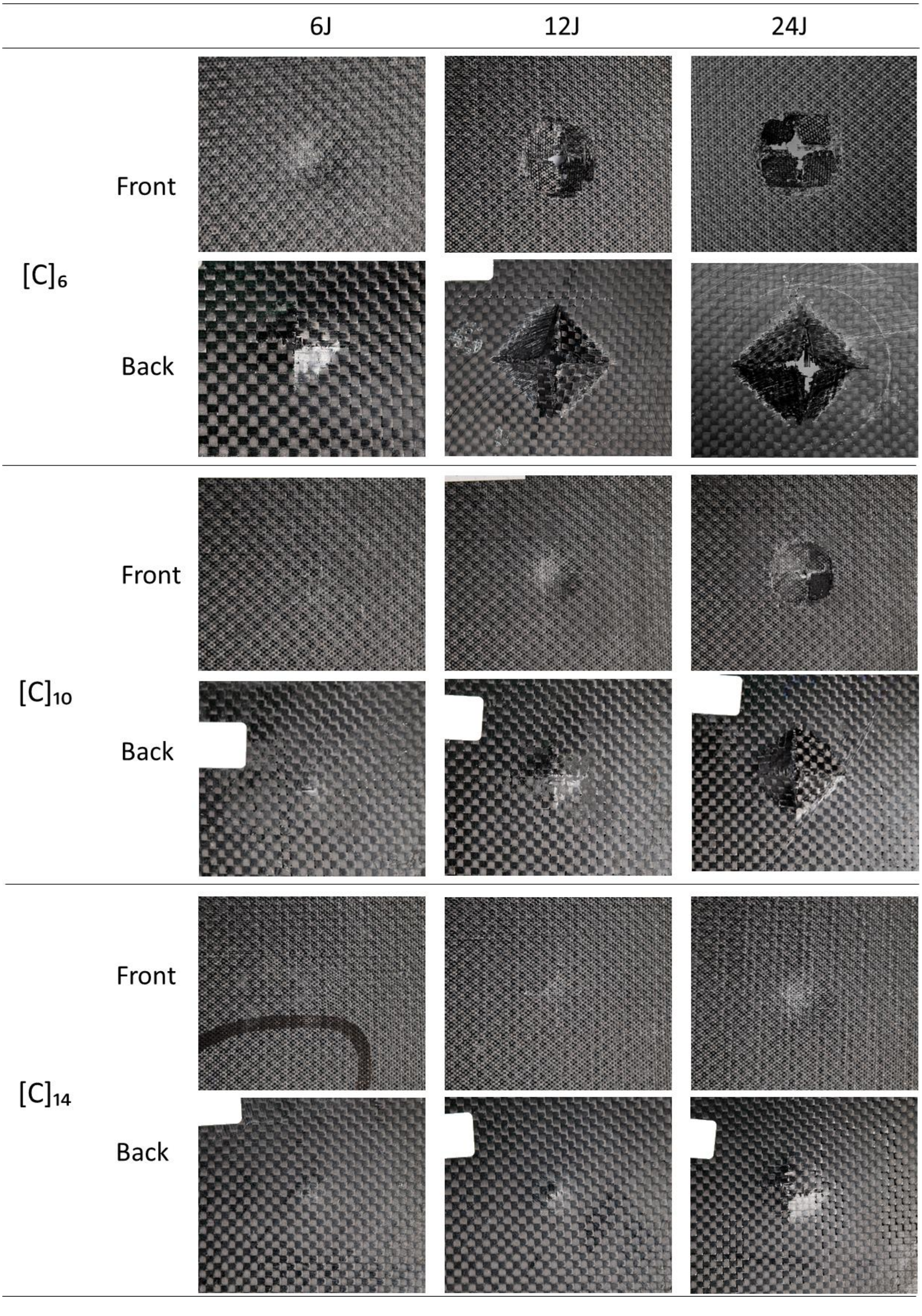

Figure 10. *Impact damage photographs of the composites with 20 mm impactor diameter*

The perforation and absorbed energy values of composites and the residual velocities of the impactors are given in Figures 11 and 12 respectively. When the energy values are examined, the effect of the damage caused by the 10 mm diameter-impactor is seen. Depending on the increase in composite thickness and impact energy, the energies absorbed in the composites also increased. As can be seen from the graphics, different impactor geometry could increase the damage leading to penetration and perforation modes. It is seen in the Figure 9 that, above the penetration energy thresholds, the energy absorbtion of the composites remains at the same level and perforation energies were lower than impact energies as in the literature [18]. When the impact energies increase, the residual velocities of the impactor also increased. As the composite thickness increased, the residual velocity decreased. In other words, higher the residual velocity, higher the damage to the composite.

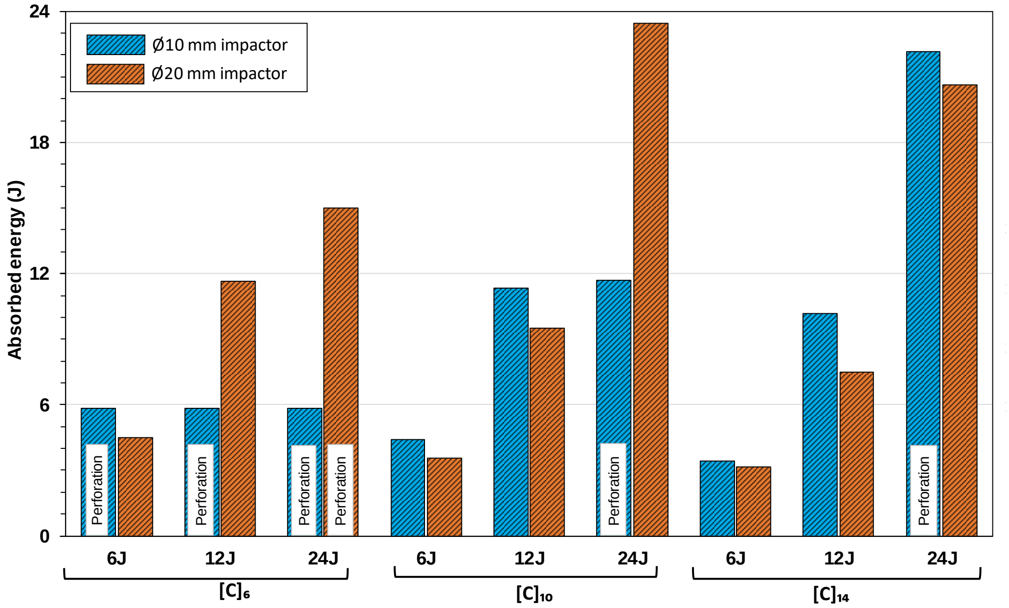

Figure 11. *Absorbed energy values of composites at 10 mm and 20 mm impactor diameters*

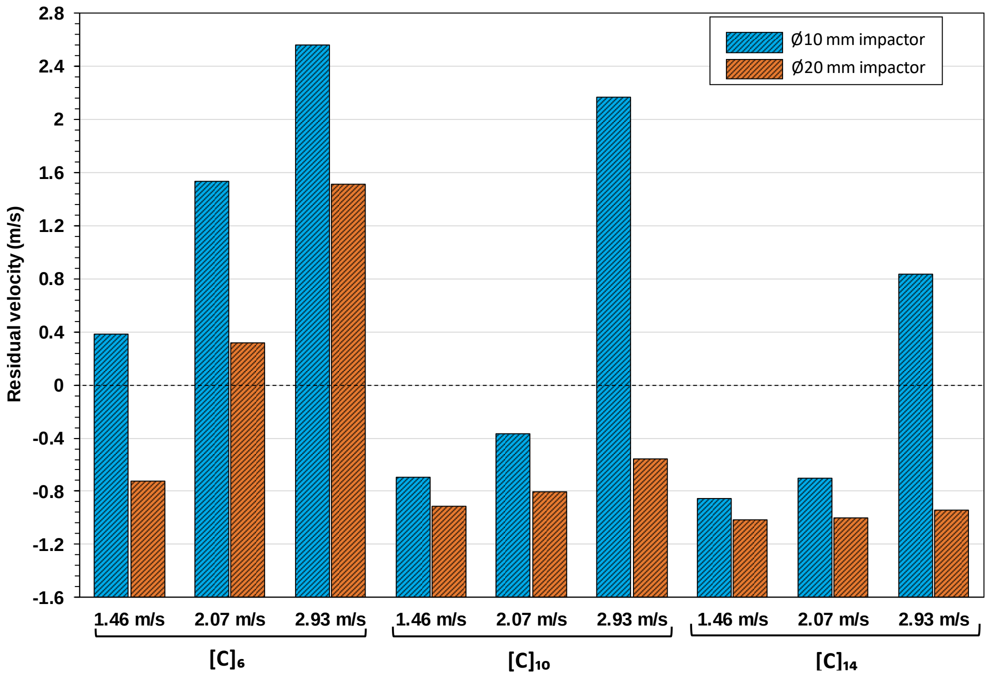

Figure 12. *Residual velocities of impactors at 10 mm and 20 mm diameters*

4.CONCLUSIONS

Effects of the ply number and impactor geometry on the low-velocity impact behavior of carbon fiber laminated composites were investigated in this study and following results are obtained: Increasing brittle fiber ply made the composites more rigid against to energy absorbtion capabilities. Increasing impactor diameter decreased the displacaments. Maximum forces increased with increasing composite thickness and increasing impactor diameter. Increasing impact energy increased the damage areas. Due to the increase in the diameter of the impactor, the damage sizes of the composites decreased and increasing impactor diameter increased the damage threshold of the composites. It has been seen that impactor geometries determine the failure mechanisms. In future studies, the effect of temperature and the effects of layer thickness and impactor geometry on pure or hybrid composites would be investigate with using more ductile fibers than carbon fiber.

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